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THEORIES OF METALLIC CONDUCTION OF ELECTRICITY WITH EXPERIMENTS ON THE CONDUCTIVITY OF A ROTATING COIL

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY CLARENCE CARL SCHMIDT

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARTS IN PHYSICS

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I INTRODUCTION

How does an electric current pass through a metallic wire? This most common of electrical occurrences presents an unsolved fundamental problem in electrical science. In the passage of the current through electrolytic and gaseous conductors, the theories seem fairly complete and satisfactory. Experiments have shown that the electric current carried through electrolytes and gases is accompanied by the transfer of material particles or ions and it has been proved by varied and ingenous experiments that the electric transfer is a convection process.

For metallic conduction, there is as yet no explanation which may be regarded as at all adequate and complete. It is the purpose of this paper to present and discuss the various theories of metallic conduction and to describe a new experiment which has given results that seem to be of importance in the problem.

II EARLY THEORIES

Probably the first theory of metallic conduction was formulated by Wilhelm Weber (54) who assumed that two equal streams of positive and negative electricity flowed in opposite directions. The electricity would continually be accelerated by the electromotive force, if there were no resistance. This resistance according to Weber is caused by the attraction of the opposing electrical masses. If now a positive and a negative particle approach each other there will be an attraction, between them, similar to that between two bodies attracted by gravity. The particles will under such action describe spiral paths about a common center. The applied electromotive force causes the paths of the rotating system to be drawn out longitudinally so that the particles come into the sphere of influence of

neighboring systems to which they escape. New systems are thus formed and by a continuous process the electric current is carried through the length of the conductor.

Herwig (35) conceives the stream of electricity as a movement of the electrical particles from one molecule to another and the resistance as the force of opposition encountered in moving from one atom to another. This involves a change in the amplitude of vibration of the particles as well as a movement in the direction of the electromotive force. Both of these phenomena require a certain amount of work;since the movement of the particles carrying the current requires that the amplitude change also, and since heating of the conductor increases the energy of vibration, then heating should increase the resistance of a conductor.

Another theory of metallic conduction of electricity was that the charge was carried by molecules, but in the case of dense solids, such as the metals, such a process is hardly conceivable, since nothing as large as a molecule could pass through the metal with such ease as must be the case, because the forces required to send a current through a wire are small.

From this it is seen that some other carrier must be found to account for the passage of a current. Giese (10) was one of the first to form a different theory. He argued against the molecular transfer theory, since if molecules were acting as the carriers there must be a large amount of matter carried with the current. It had been determined previously that the passage of electricity through flames was by means of charged atoms, hence it was argued that atoms might perform the same office of carriers in the case of metals. In order to produce the same effect by means of a charged molecule

several thousand times (at least 1700 times in the case of hydrogen) as much more matter would have to be transferred as in the case where the ions are given this property.

Furthermore, he shows that the molecule cannot be electrified. Water is an example which readily shows this. Distilled water has very high insulating properties, but when used as a solvent its ions according to Giese become highly conducting.

According to his theory, a given substance or metal may have atoms which are exactly alike except for their charges, for instance, Cu_+ and Cu_-. The property of being a conductor or a non-conductor depends upon the relative number of each kind. The molecules may exchange ions and thus the excess charges will find their way to the surface.

When two metals are placed in contact, the excess ions on each tend to neutralize each other. An e.m.f. would then be produced, the magnitude of which would depend upon the kind of metals that were placed in contact. These excess ions were termed "free ions" on account of being free to move about and thus carry the current. The difference between metallic and electrolytic conduction is that in the latter, the ions bodily carry the charge from place to place, while in the former, the charge is passed along by the interchanging of ions between the molecules. The metals being of denser material, the molecules are bound to remain in one place and are not free to move as in the case of the electrolyte; hence, there is merely a shift of ions from one to the other.

The difference, according to this theory, between conductors and insulators is, that the latter have no free ions, or that each ion is bound to a particular molecule and cannot change to another.

A change in the resistance indicates a molecular change such that the metal either becomes more conductive, or offers more resistance according as the number of free ions becomes greater or less.

Such a theory tho explaining some things very well was far from satisfactory. Numerous experiments were made to determine whether there was any transfer of matter with the passage of a current. Two metals were placed in contact and a current passed through them for a long time, in one case for the space of a whole year; but no trace of either metal could be found in the other.

These earlier theories have, of course, been antiquated by the discovery of the electron. They are , however, important in being the direct forerunners of our present electron theories of conduction. Indeed, when these earlier theories are translated into the language of the electronic theory, they are very suggestive and in some cases show anticipation of our more recent ideas.

III. ELECTRONIC THEORIES OF CONDUCTION

The study of the conduction of electricity through gases which was extended about this time threw new light upon the subject, especially when the electron was discovered by J.J. Thomson and others about 1897. It was shown that this was the basic particle of electricity which might move and carry the current through the metal. Its small size, high velocity, and the fact that electrons are the same in every metal made it the logical carrier of electricity.

Riecke (24) carries out an idea expressed, though not developed by Weber (34) who stated years before that the molecules of a metal were surrounded by moving molecules or particles of electricity.

These particles Riecke identifies as the electrons or corpuscles discovered through the work of J.J. Thomson and others.

Drude (8) added considerable to the ideas of Riecke and showed a marked similarity between these ideas and the ideas expressed by Giese. The properties of carrying the current ascribed by the latter to the ion, Drude points out belong to the electron, the charge unattached to any matter. These electrons seem to obey the kinetic theory of gases and hence Drude's theory is known as the "free gas" theory.

Since metals are the best conductors of both electricity and heat, the electron must play a part in the conduction of both heat and electricity. The fact that electrons of one metal do not differ from those of another strengthens this viewpoint. When the coefficients of thermal and electrical conductivities are compared there is found to be a constant ratio between them. This had been noted many years before and is known as the Wiedemann - Franz' (28) ratio; questions have been raised about the significance of this ratio, but it has been shown to be a fact both theoretically and experimentally. There is also a marked parallelism between the change of thermal and electrical conductivity with temperature.

A gas is considered as having molecules moving in all directions and if the number is taken as N, then in each of the six directions parallel to the three axes there are N/6 moving with a velocity v. Each molecule has a momentum +mv on striking a surface and -mv on rebounding from it. The pressure on the surface is $Nv/6 \times 2mv$ or $P = 1/3\ Nmv^2$. Nm is the mass per unit volume of gas or the density.

But, pressure x volume = RT

or $1/3\ Nmv^2 = RT.$

This shows that the kinetic energy is proportional to the absolute temperature or $1/2\ mv^2 = \alpha T$ where $\alpha = 3/2\ R/N$. Thus when electrons in a conductor are in temperature equilibrium the velocity may be found from the kinetic theory.

The acceleration of an electron after collision is $f = \frac{Ee}{m}$ where E is the electrical intensity. The average distance traveled by an electron, or the mean free path is λ, hence the distance traveled due to the acceleration, f, is

$$\frac{1}{2}\frac{Ee}{m}\frac{\lambda^2}{v^2}$$

where $\frac{\lambda}{v}$ is the time taken to traverse the mean free path in the direction of the field. The average velocity in this direction is

$$\frac{1}{2}\frac{Ee}{m}\frac{\lambda^2}{v^2}\frac{v}{\lambda} = \frac{1}{2}\frac{Ee\lambda}{mv}$$

but $\frac{1}{2}\ mv^2 = \alpha T$ or $m = \frac{2\alpha T}{v^2}$

Therefore the average velocity in the direction of the field is $\frac{E\ e\ \lambda\ v}{4\alpha T}$.

The corresponding current, is Ne times the velocity where N is the number of electrons per unit volume, or

$$\text{current} = \frac{Ne^2 E\lambda v}{4\alpha T} = i$$

and conductivity, $\sigma = \frac{i}{E} = \frac{Ne^2\lambda v}{4\alpha T}$.

It follows that Ohm's law is obeyed, for the conductivity is independent of the current and further the conductivity is inversely proportional to the absolute temperature.

In a very similar way the thermal conductivity k, is found to be

$$\frac{Nv\alpha\lambda}{3}$$

The ratio of k/σ is then given as

$$\frac{\frac{Nv\alpha\lambda}{3}}{\frac{Ne^2\lambda v}{4\alpha T}} = \left(\frac{\alpha}{e}\right)^2 \frac{4}{3} T$$

Experimental results show that this ratio with very few exceptions is constant, and its value is given as 6.5×10^{10}.

When an electric force is applied there is a drift of electrons in the direction of the force. If the parts of the metal are at different temperatures the heat will flow from the hotter parts to the cold. If the greater part of the heat conductivity is due to electrons the thermal conductivity should bear a constant ratio to electrical conductivity.

If an electric current passes through an unequally heated metal, electrons will drift from places of high potential to low potential and carry heat with them; thus the passage of a current through a conductor will alter the flow of heat. This is known as the Thomson effect discovered by Sir Wm. Thomson, Lord Kelvin.

J.J. Thomson (30) in noting the effect of temperature on the resistance of metals finds that the free gas theory is inadequate. If the electrical conductivity is due to free electrons, changes in conductivity are due to two factors, n, the number of free electrons and, k, their mobility. The product of n and k, if the conductivity is inversely proportional to the absolute temperature, must be greater at low temperatures than at high. Since n is proportional to $e^{-\frac{W}{RT}}$ where T is the absolute temperature temperature and R the gas constant, and, since this factor decreases at low temperatures, then the increase in nk must be due to k, or the mobility of the system. But this he finds must also decrease with lowering temperature.

Experiments by Kammerlingh Onnes (29) with metals at low temperatures seem to contradict the free electron theory. He found that the resistance of pure metals, such as lead or mercury, at the temperature of liquid helium becomes so small that it cannot be measured, or less than one thousandth-millionth of its value at 0°C. In the case of a lead ring a current started by moving a magnet up to the coil will continue for some time without any very noticeable decrease if the low temperature is maintained. In fact, it was estimated that the current would continue for four days before it would fall to one half its value.

In view of the difficulties thus involved in the free gas theory, Thomson (29,31) introduced another, analogous to the molecular theory of magnetism. He shows in this that the presence of a negative charge means that there is also an equal positive charge. Each molecule of the metal has an electric dipole consisting of equal and opposite electric charges a short distance apart. When an electric force is applied these dipoles align themselves in chains extending in the direction of the electric force from one end of the conductor to the other. These doublets will produce strong electric forces which will tend to pull the electron from one atom to another. The difference between a conductor and an insulator lies in the power to resist the electric force. In the case of metals this is much less than in the case of insulators.

The superconductivity noticed by Onnes (30) in which the resistance drops down very suddenly to practically zero may be explained in that the electric force polarizes the dipoles in the metal, which then remain in that state when cooled, even though the electric force is removed; hence, the current will still persist.

In measuring the effect of increased pressure in twenty two metals Bridgeman (2) found that with the exception of two, namely, antimony and bismuth, the increase in pressure tends to decrease the resistance. He found, however, that, though under pressure of, say, 12,000 Kg and at a temperature of 0°C the volume is smaller than at 0° absolute. Nevertheless, the decrease in resistance at that pressure is a very small percent of the change in resistance brought about when the metal is cooled to 0° absolute, a point toward which the resistance tends to approach zero. In the case of the two abnormal metals mentioned the change in volume due to pressure of 12,000 $\frac{kg}{cm^2}$ is almost three times the change in volume due to cooling to 0° absolute.

In regard to the theory of Drude, Riecke and Lorentz, which expresses the conductivity in the form

$$\text{conductivity} = \text{constant } \frac{lu}{N}$$

or

$$\text{conductivity} = \text{constant } \frac{T^{1/2}}{N}$$

where N is the number of electrons per cubic centimeter, l, the mean free path, u, the velocity, and T, the absolute temperature, Bridgeman (6) says it fails to account satisfactorily for specific heat, the variation of resistance with temperature, and the negative pressure coefficient at constant temperature. The values of N, l, and u, cannot under any circumstances be conceived as changing enough to account for the change in resistance. According to J.J. Thomson's doublet theory the conductivity is given by

$$C = \frac{1}{3} \frac{NepdM}{KT}$$

where N is the number of doublets per cubic centimeter, p, the number of electrons emitted by an atom per second, M, the moment of the

doublet, K, the gas constant, and d, the distance between the centers of adjacent atoms. Part of the increase might be accounted for a change in N. But, according to Richardson, N for tungsten at 2000° is 1.7×10^{16} which tends to be the minimum value, and this number is much too large to justify the equation; hence, he concludes that this theory is inadequate.

The equation developed by Grüneisen (11) is the only one which in any way provides for pressure effects. It is given as

$$\frac{1}{u}\left(\frac{\partial u}{\partial P}\right)_T = \frac{1}{u}\left(\frac{\partial u}{\partial P}\right)_s + \frac{1}{N}\left(\frac{\partial N}{\partial P}\right)_s + w_s - \frac{1}{c_p}\left(\frac{\partial v}{\partial T}\right)_P \left[1 + \alpha_T T\right].$$

in which u is the velocity of the electrons and $\frac{1}{u}\left(\frac{\partial u}{\partial P}\right)_s$ is a relation between pressure and velocity which is unknown. The electrical resistance of a pure metal is proportional to a universal function of T/ v_m where v_m is determined by the atomic temperature. Grüneisen found that the experimental results of Lissell, Williams, LaFay, Beckman, Chwolson, Tomlinson and others agree with this equation.

According to this theory of Grüneisen the movement of the electrons increases with the compression of the atoms while the amplitude of vibration decreases. This is also the viewpoint of Bridgeman who states also that the change in resistance may be due to a change in the amplitude of vibration of the atoms.

He proposes a different theory for the resistance offered to the passage of electrons. In the free gas theory this is explained as due to the friction of the electrons, or the collision of the electrons with the molecules. Wien thought of it as caused by the collision of the electrons with the positive neucleous.

Bridgeman (6), on the other hand, departs radically from this and says that no resistance is offered to the electron as it passes through the molecule, but that the resistance is explained as due to

a force which is required to move the electron from one atom to another. He calls this the "gap" theory. He shows that the electron encounters difficulty in getting away from the atom, as may be seen from the fact that there is a definite ionizing potential in the case of a gas. This force which tends to act against the passage of an electron from atom to atom is less, the smaller the mean free path, and since this depends upon the amplitude of vibration, then the amount of resistance can be traced directly to this amplitude of vibration.

The classical expression for the resistance $R = \frac{2mv}{e^2nl}$ will hold where, e is the charge, and v the velocity of the electron. Ohm's law can also be explained by this theory.

In support of this theory Bridgeman shows that where the metal changes the state of aggregation as in melting, the state which has the smaller volume has the least resistance. This is shown to be true not only in the case of metals which act normally upon melting, but also for those in which abnormalities occur as in Bi, Sb, and Ga, in which the liquid has the lesser volume and the smaller resistance. He holds that this is more easily explained from the "gap" point of view than from Wien's in which collision with the atomic center forms the basis of explanation.

He points out that in the classical theory l, and v were determined, but n was made to fit as the case demanded without showing sufficient reason for the change in n. In the gap theory variations in v and l are accounted for; hence, there is no necessity for changing the value of n, which is therefore assumed to remain constant.

Bridgeman applies the "gap" theory to a number of different effects to show that it is not inconsistent with a number of facts which have been explained by various, and in most cases, well

established theories.

This theory also gives a consistent explanation of the resistance of alloys. Of these there are two kinds, those which form mixed crystals and those which do not. In the latter case separate crystals are formed of the two metals and the resistance may be computed from the rule of mixtures. In the other case, however, mixed crystals are formed which combine best according to certain proportions of the two components. That in some cases an imperfect fitting of these different shaped crystals would tend to make the gaps larger and thus increase the resistance can easily be deduced. In such a case the resistance of an alloy might be greater than either of its component parts. That the alloy is not affected so much by changes in temperature is explained by assuming that the imperfect fitting of atoms persists as the temperature is decreased.

Hard drawing increases the resistance of metals and is explained as due to the breaking up of the crystal grains and thus making the atoms fit more imperfectly. This explanation seems adequate even though the density decreases when the metal is hard drawn.

Hardness is caused by a staggering of atoms, hence the increased resistance is due to a greater separation of atoms, which is in accord with the facts.

In the case of solid bismuth and antimony which are abnormal, the increase of resistance per degree rise in temperature is normal. This is because the effect of temperature overshadows any pure volume effect so that the temperature coefficients are nearly the same for all metals irrespective of the pressure coefficient. That liquid bismuth behaves normally is probably due to the fact that the crystal structure is broken down and then the metal acts like any other.

In none of the work done by Bridgeman was anything found that would seem inconsistent with the "gap" theory. This, however, seems to have wonderful elastic possibilities so that any case may be explained without actually contradicting the theory itself.

Though not referred to by Bridgeman, F. Credner's (7) work on the effect on resistance of twisting, bending and drawing would further lend weight to this view. From a large amount of data he found that each of these operations greatly increases the resistance. Tammann who did similar work gives a three fold explanation: formation of space between individual crystalline units, the alteration of the structure in the case of stretching, and formation of spaces on the gliding surfaces in the case of twisting.

IV. EXPERIMENTS WITH MECHANICAL FORCES ON ELECTRONS

Various attempts have been made to throw additional light upon the subject of metallic conduction of electricity by means of experiments in which mechanical forces are exerted upon the electrons. The earliest of these were made when the ionic theories of conduction prevailed. I. Bosi (quoted by Hall (12)) in 1877 used electrolytes of sulphate of zinc and sulphate of copper which he caused to flow with a velocity of 10 to 12 cm. per second. He reported that there was considerable difference in the resistance when the current flowed in the direction of motion and when it flowed in the opposite direction.

J.B. Haywood (12) of the Harvard Graduate School, repeating the experiment under Professor E.H. Halls' supervision, found that no such large effects could be detected and indeed if any effect existed, it was exceedingly small.

A similar experiment with electrolytes of different kinds was performed by J. Nabl (19). His results show that there was practically no change in the resistance due to changing the direction of the current with respect to the movement of the electrolyte.

Tolman, Osgerby, and Stewart (32) used an acceleration method. A tube was filled with potassium iodide and suddenly accelerated which set up a difference of potential between the two ends. When such a tube was placed around the rim of a bicycle wheel and quickly started a current was set up. This is explained as due to the fact that the negative iodide atoms are heavier than the positive potassium ions and thus set up an e.m.f. opposite to the direction of rotation.

E.F. Nichols (20) brought forth a new aspect by rotating a disk of aluminum on which contacts had been made at the center and the outer edge. The object of this experiment was to determine from the e.m.f. developed and the change in resistance, whether the positive or the negative charge was bound in the case of metal. Since the ratio of e/m is different for positive and negative particles, the mass must be different, which would then give different centrifugal forces to each. His apparatus did not prove sensitive enough to enable him to detect results which would verify his theory that negative ions were the carriers of electricity. Various heating effects also proved to be complications, obscuring any positive conclusions.

The acceleration method was used by Tolman and Stewart (32) with metals. Their former apparatus was modified by replacing the tube filled with an electrolyte by a coil of wire. When this was rotated and suddenly stopped there was a "kick" in the connected

galvanometer, explained as due to the momentum of the electrons. The experimental results seem to warrant the acceptance of the free electron theory rather than the doublet theory, for it is more probable that free electrons could be given a momentum than that such acceleration would in any way produce action on electric doublets.

Two years previous to the work just described an experimental investigation was carried on in the Physics Laboratory of the University of Illinois by Paul L. Bayley (1). In this work the coil was rotated uniformly and the change of resistance caused by rotation noted. The results were quite small and could not be determined very accurately; though in general the resistance was larger when the coil was rotating. Experimental difficulties in the form of poor contact of the measuring instruments with the rapidly moving parts were not encouraging for further experiments, until better methods of connection could be devised.

V. EXPERIMENTS BY THE WRITER

It was the purpose of the present experiment to remove the difficulty involved in the contact and to extend, if possible, the results obtained by Bayley. It was hoped thus to obtain additional data which would disclose more concerning the mechanism of metallic conduction.

The coil consisted of a large number of turns of insulated copper wire, No.25 B.& S., which was wound in a groove in the edge of a disk made from one-inch compressed fibre. The average diameter of the coil was 28.5 cm. Each layer of wire was covered with shellac and allowed to dry before the succeeding layer was wound, thus insuring perfect insulation with all the wires rigidly bound together.

The ends of the wire were attached to plates on either side of the disk which in turn were rigidly attached to the shaft of the wheel or disk. The shaft was cut at the middle, so that the two ends were insulated from each other. The arrangement of the various parts are shown in Fig.1.

In order that there might be no possible magnetic effects, all parts of the disk and bearings were made of non-magnetic substances, brass was found best adapted for the metal parts. The axle itself turned in babbitt bearings which were set on dry wood pillars and completely insulated from each other. On the outer end of the shaft a pulley was attached to which a quarter inch leather belt transferred the power from a two-phase, 60-cycle, 440-volt induction motor which was used in order to prevent any possible electromagnetic induction effects.

In the apparatus used by Bayley the contact with the revolving parts was made by means of a mercury fountain attached to a hollow tube all parts of which were amalgamated, this tube acted as a brush to collect the current. This contact was found to be very unsatisfactory by Bayley particularly at high speeds, because thermoelectric forces were produced and it was also variable in action. Another method was therefore used in the present experiments. A tapering hole was carefully drilled along the axis of the shaft at each end and into this a brass plug which could easily be removed was fitted. At the center of the plug a copper wire, No.25 B.&S., was soldered. This wire extended outward in line with the axle for a distance of fifty feet and twisted upon itself when the coil was set in motion. This is the method used by Tolman and Stewart. In this experiment where change in resistance was to be noted instead of an e.m.f. or an

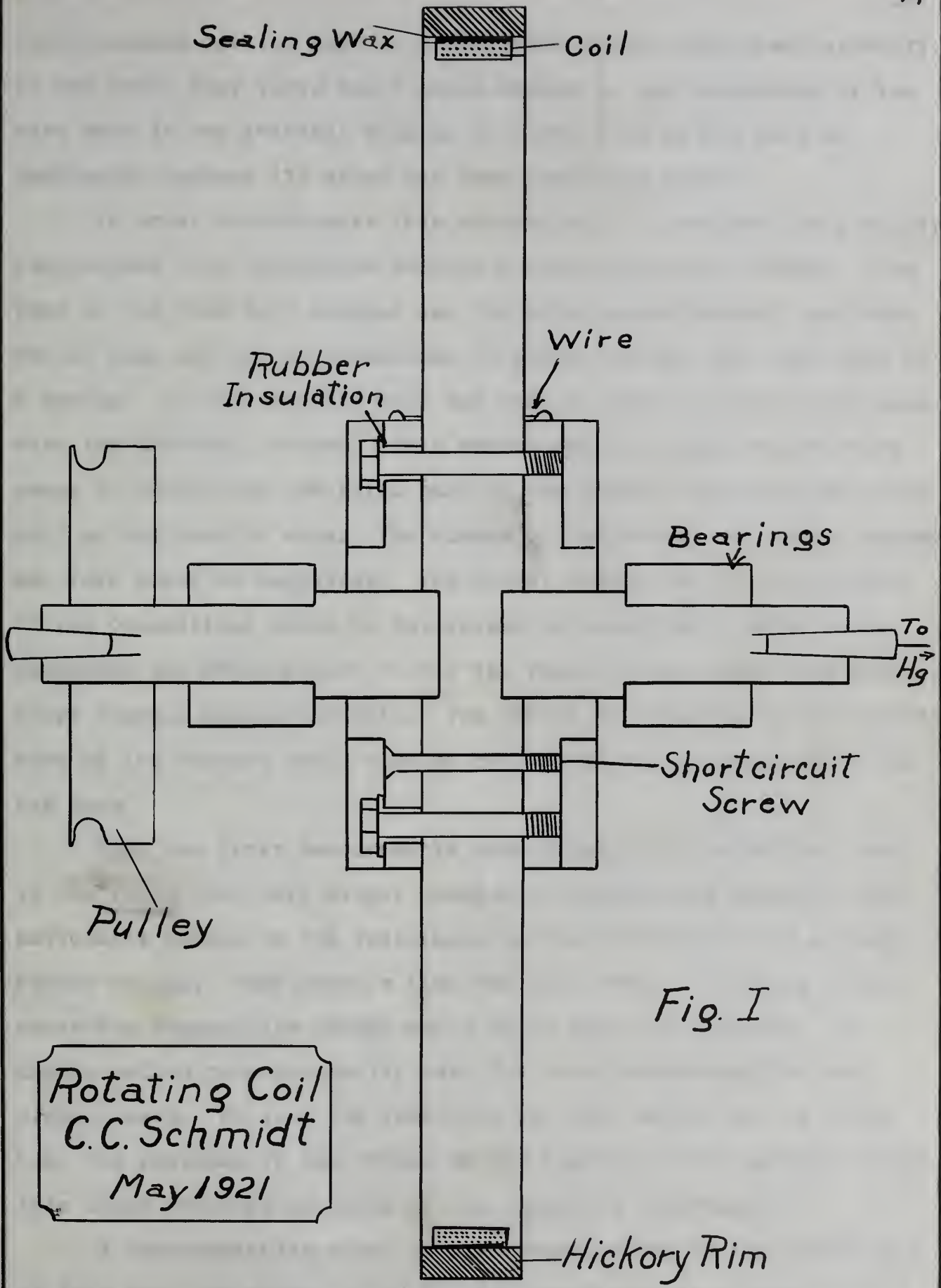


Fig. I

Rotating Coil
C. C. Schmidt
May 1921

Fig 1

Rotating Coil
C.C. Schmidt
May 1921

instantaneous current such an arrangement proved very unsatisfactory. It was found that there was a large change in the resistance of the wire when it was twisted; this as is shown also in the work of Tammann and Credner (7) which has been mentioned above.

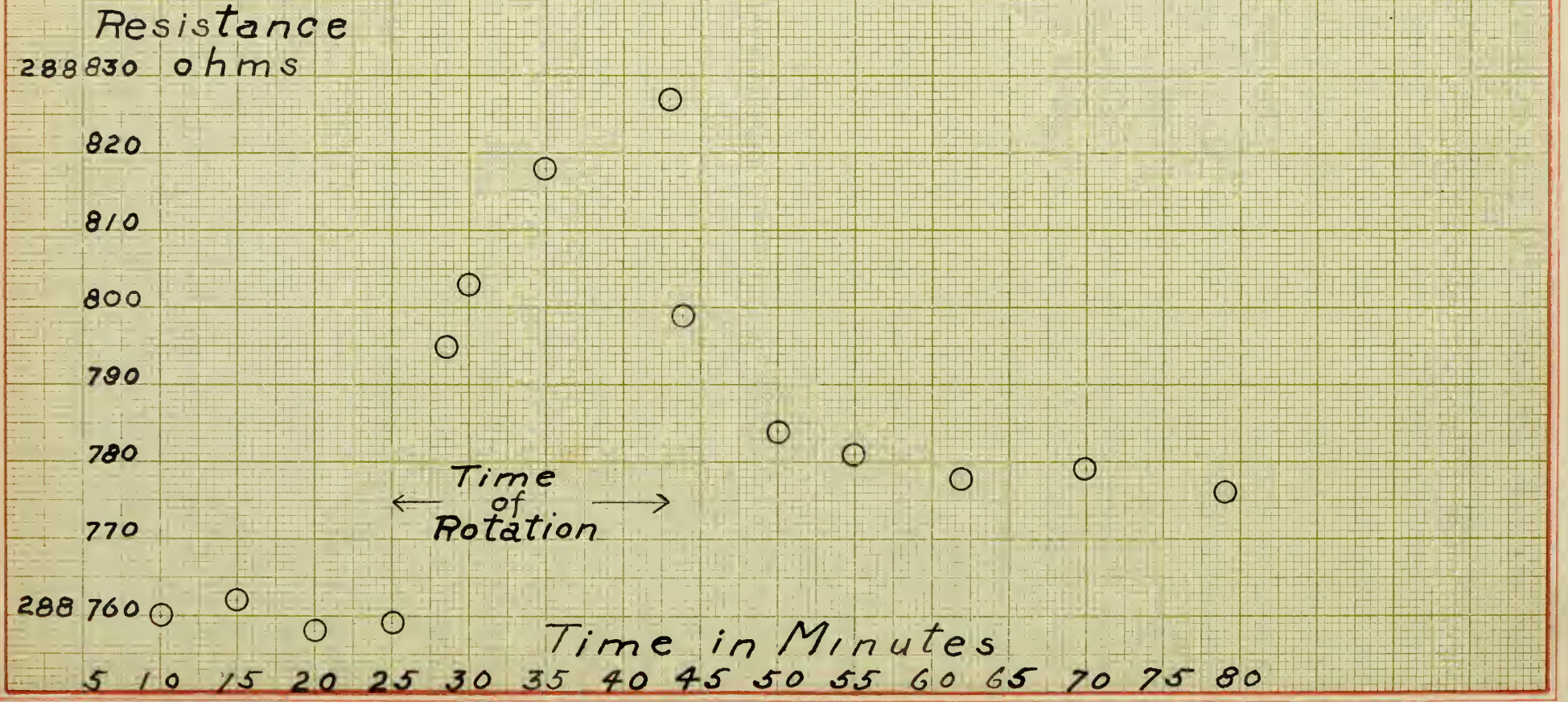
In order to eliminate this effect the wire was made only thirty centimeters long and passed through a tube containing mercury. The ends of the tube were stopped and the wire passed through the stopper at each end and then fastened to a small swivel and kept taut by a spring. In this way the wire was made to spin in the mercury bath when the disk was rotated. This device proved a very satisfactory means of connecting the fixed part of the circuit with the revolving coil as the results show. The change in resistance was quite constant and very small in magnitude. The actual change due to the rotation of the connections could be determined by inserting a screw which connected the brass plates on the two faces of the disk; this made a short circuit around the coil. The effect of rotation on the resistance of the contact could thus be determined and allowance made for the same.

When the first measurements were taken with the coil at rest, it was found that very slight changes in temperature caused a very noticeable change in the resistance as was determined with a Carey Foster bridge. Considerable time was then spent in finding a room where the temperature change would be as small as possible. A double walled room ordinarily used for sound determinations was finally used. To show how sensitive the coil was it may be noted that the presence of one person or the lighting of an ordinary electric light could be detected by the change in resistance .

A representative curve of the determination of the resistance of this coil are shown in Fig.2. The resistance is plotted as the

Fig II
Variation of Resistance in Copper Coil and Effect of Rotation

C.C. Schmidt
May 1921



ordinate and the time as the abscissae. It shows a gradual change in the resistance while the coil is being rotated, which was interpreted as due to temperature changes since copper has a large temperature coefficient of resistance. A second coil was made using manganin wire. The results were of similar character, but the changes were much less.

Later the manganin was replaced by 83.03 meters of "Advance" wire obtained from the Driver-Harris Company. This was not shellacked during the winding because the ordinary insulation was sufficient for the small electromotive forces used. In order to make the wire coil rigid and to guard against any possible stretching, due to centrifugal force, which would of course tend to increase the resistance, melted sealing wax was poured into the groove over the wire. After this was smoothly turned down in a lathe a hickory rim was bent into a circle and bound closely upon the rim of the disk by brass bands. In this way the wire was held rigidly in place.

When this new coil was rotated a relatively large increase of resistance was noted. Since "Advance" wire has a very small temperature coefficient, and that negative (-.0000056), such an effect could not be explained as a temperature change in the resistance of the wire. Hence, another source of the effect was sought. Since it continued after the rotation ceased it was suspected to be due to thermo-electric forces. To test this, a sensitive galvanometer was placed in series with the coil; then a heated block of brass was placed in contact with the bearing and also with the pulley. Each of these gave a deflection. By placing the heated block on the contacts between the wire and the brass plates similar results were obtained. It was evident that though the disk was apparently symmetrical, one side was heated more than the other, either by the friction

in the bearings or else by friction of the belt on the pulley. This unsymmetrical heating and the consequent thermo-electromotive force was the cause of this irregularity. Hence, the disk was remodeled.

Fig.3 shows the remodeled form of the disk. Two radical changes were made:- first the babbitt bearings were replaced by high speed ball bearings of the S.K.F. type, thus reducing the friction to practically nothing; furthermore, the brass was taken out as a metal of the circuit by drilling a hole along the axis of the shaft and another through the brass plate perpendicular to the shaft. Through this passage an insulated copper was drawn. The brass plug was removed and replaced by one of copper which was insulated from the brass shaft by a hard rubber bushing. In this way the thermo-junctions between brass and the other metals were removed. The junctions between the copper and "Advance" wire were placed on either side of the disk as near the outer edge of the disk as possible. It would be very unlikely that under these conditions the two junctions would be at temperatures noticeably different. In fact, no thermo-electric forces existed at these points after these changes were made. In order that the coil could be short circuited a fine copper wire was soldered to the plugs, which could be connected to small screws near the ends of the shaft.

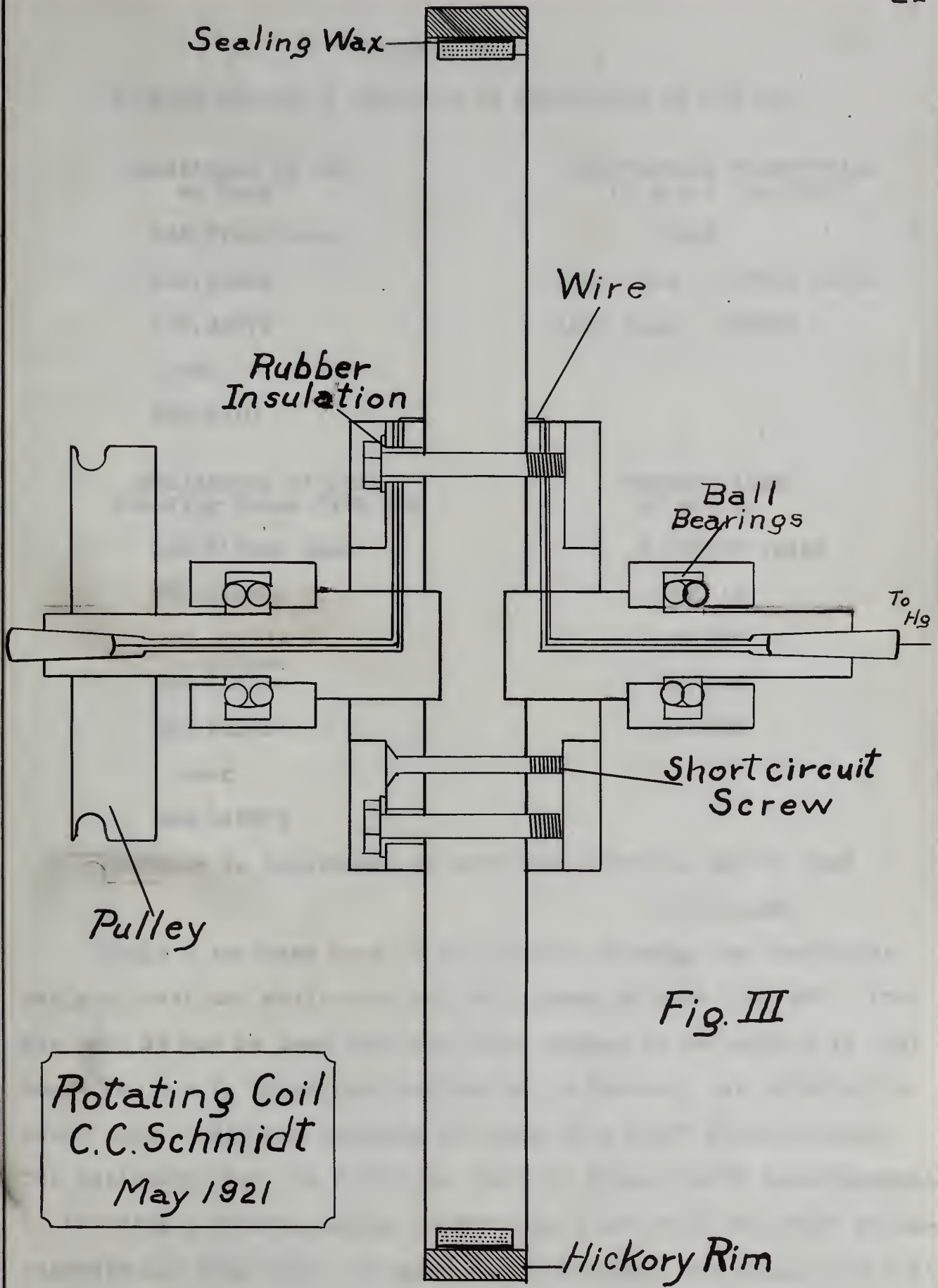
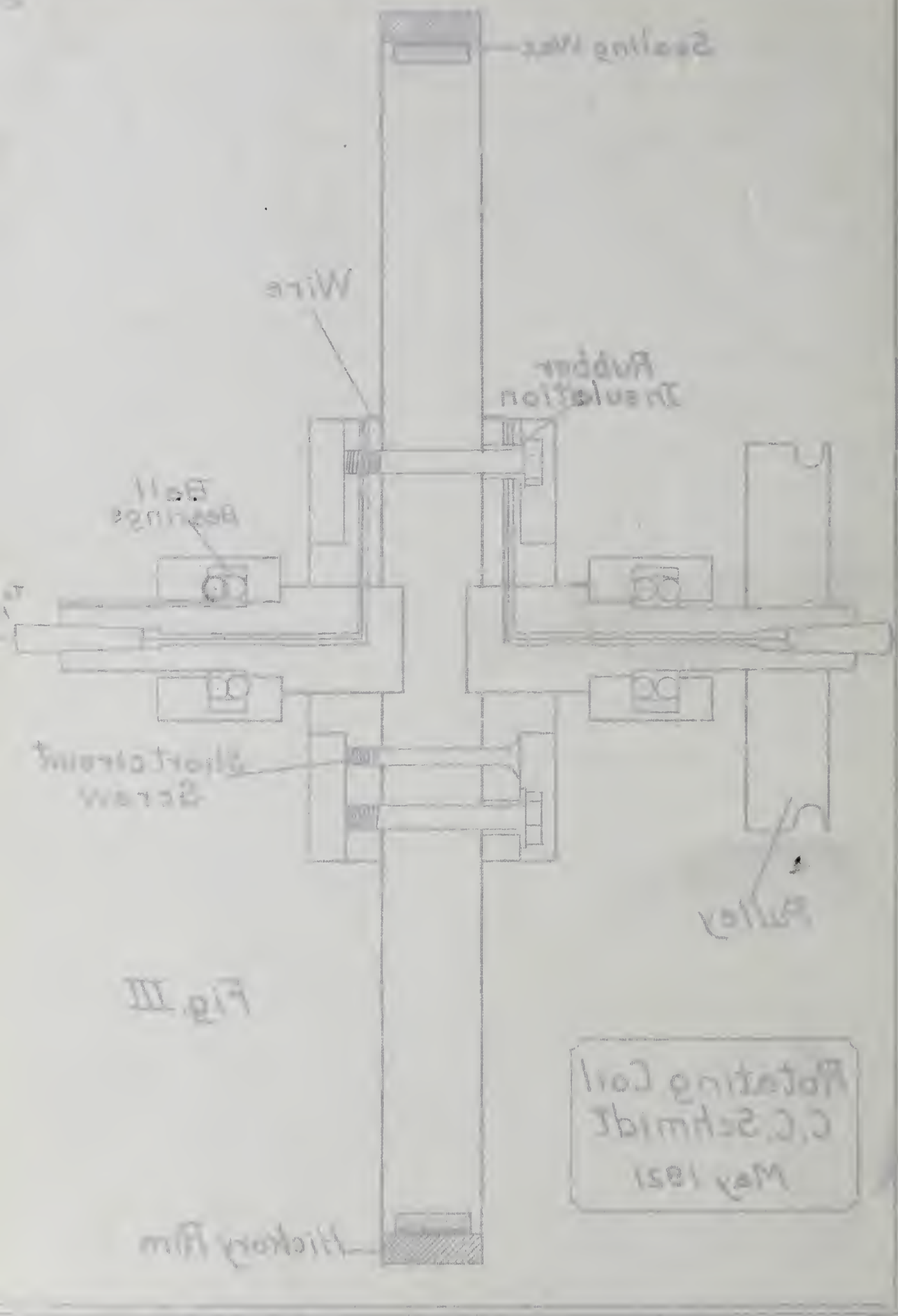


Fig. III

Rotating Coil
C.C. Schmidt
May 1921


Sealing Wax
Wire
Rubber Insulation
Ball Bearings
Short circuit Screw
Pulley
Hickory Rim
Rotating Coil
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May 1921

Fig. III

TABLE I

SHOWING EFFECT OF ROTATION ON RESISTANCE OF THE COIL

Resistance of Coil at Rest	Simultaneous Observation of e.m.f. in volts
235.87904 ohms	None
235.88446	less than -.000005 volts
235.92873	less than .000005
Mean	
235.8970	

Resistance of Coil Rotating Speed 7188 RPM	Observations of e.m.f.
236.218345 ohms	+.000015 volts
236.216986	.000015
236.217893	.000007
236.216990	.000006
236.221055	.000015
Mean	
236.218073	

Increase in resistance of coil when rotating and at rest .3210 ohms.

Table I includes some of the results showing the resistance while at rest and while rotating at a speed of over 7000 RPM. From the data it may be seen that the total change in resistance is .321 ohm. The e.m.f. which was produced while the coil was rotating is shown also. This was measured by means of a Wolff potentiometer. The resistance and the potential could be found almost simultaneously by throwing a switch, making connections first with the Wolff potentiometer and then with the Carey Foster bridge. The reason for noting

the e.m.f. was to have a check on any thermo-electric forces which might be present.

There seems no direct relation between this change of resistance and the small e.m.f. which was detected. It is thought that these were largely due to contacts outside of the disk for similar effects were noted when the coil was short circuited. In order to determine what influence these electromotive forces might have on the resistance, the current in the Carey Foster bridge was reversed; the effect of this is shown in Table II.

TABLE II

SHOWING EFFECT OF REVERSING BATTERY OF CAREY FOSTER BRIDGE

Current Direct	Current Reversed	Difference	e.m.f. Observed
Resistance of Coil at Rest			
235.92873 ohms	235.92873 ohms	0	0
Resistance of Coil Rotating 7188 R.P.M.			
236.21834 ohms	236.21608 ohms	.00226	.000015 volt
236.21789 ohms	236.21699 ohms	.00090	.000015 volt
		Mean .00155 ohm	

Since the e.m.f. was always in the same direction this shows that the maximum change in resistance due to this source is only .00226 ohm and that this is actually twice as great as the true effect, for here a difference was taken between the resistance plus the effect and the resistance minus the effect of the e.m.f. The true value for the maximum value observed is only .00113.

To make further correction the resistance due to the mercury contact must be considered. The actual resistance of the system when the coil is cut out by the short circuiting device is .20271 ohm when at rest, and .213099 ohm when the wheel is rotating,

showing that a change of .010828 ohm is due to the contact alone.

Deducting these two measurable effects from the observed change in resistance the data may be summed up as follows:

Gross change in resistance		.3210
Change due to e.m.f.	.00155	
Change due to contacts	.010828	
	.012378	.012378
Corrected change in resistance		.309622 ohm

which is a change of 1.28% of the total resistance of the coil.

While these observations were being made with the Advance wire coil, the original copper coil was changed and the connections made independent of the brass parts. It was found, however, that this was so sensitive to temperature changes due to the high temperature coefficient of copper, that no reliable results of the effect of rotation could be obtained. When it is considered that the linear velocity of the coil is about 225 miles per hour, or 105 meters per second, the tremendous amount of air friction may be realized and it is thought that the greater part of the change in resistance (over 4 ohms was observed) was largely due to a heating effect. That there was no thermo-electric effect was shown from the fact that the electromotive force measured with the potentiometer was very slight.

The elimination of this temperature effect is very desirable and it may be possible, though at present it offers the chief difficulty in the determination of the effect of rotation on the resistance of pure metals.

One possible source of error whose weight could not be determined was, that though all precautions were taken to make the wire coil rigid, there is a possibility that the disk as a whole expanded

thus causing a stretching of the wire which would undoubtedly increase the resistance. But with the disk, made up as it is with heavy brass plates on each side for a quarter of the diameter, and finally bound with outer rims of sealing wax and hickory, it hardly seems possible that there is any appreciable stretch of the disk. Tests must, however, be made for any possible stretching effect.

VI. SUMMARY AND CONCLUSIONS

1. A method has been devised by which practically constant electric connections can be made with a coil revolving at a speed of over 7000 RPM. The change in resistance from rest to full speed due to this contact is a very small amount,- in this case only .0108 ohm.

2. The thermo-electric forces produced in the system have been reduced to a very small, practically negligible quantity. In the final results 1/3% of the total change of resistance could be traced as possibly due to thermo-electric forces.

3. It has been shown that the resistance of a coil of Advance wire is increased by rotation at a speed of 7000 RPM. The change of resistance when allowance is made for other known effects is .309 ohm, or 1.28% of the total resistance. The centrifugal acceleration in this case is 763,000 cm. per sec. per sec.

4. Experiments, similar to those made with "Advance" wire, with a copper wire showed temperature effects too great to allow any deductions as to the effect of rotation alone. The elimination of this temperature effect is the next step, as it is very desirable to get results with a pure metal.

5. It is not easy to analyze the results of this experiment

as to its bearing upon the theory of metallic conduction, because it does not point conclusively to any one of the theories advanced. The results are, however, more easily explained on the "free gas" or the "doublet" theory than on the "gap" theory.

a. If we are to accept the free electron theory, then the change of resistance might be explained by assuming that the electrons are thrown to the outer portion of the conductor, thus producing a crowding or condensation of the electrons, which would cause an increase in the number of collisions or the friction between the electrons and the molecules.

b. According to the doublet theory such a force might tend to depolarize the dipoles or to throw the chain of doublets out of line which would cause the resistance to become greater.

c. If a stretching effect of the wire could be detected then such a change in resistance might be explained from the "gap" theory which seems to cover quite extensively the changes of resistance due to changes in the structure of a metal. But the possibility of a stretching of the coil, as already noticed, seems to be very small. If the increase is due to a pure rotation effect then it is hard to see how it can be explained on any "gap" theory.

The fact, that the results obtained are entirely from "Advance" wire which is an alloy and hence involves factors not present in pure metals, prevents definite conclusions as to the effect of a similar experiment upon a pure metal.

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VII. BIBLIOGRAPHY

1. Bayley, P.K.

Electron Theories of Metallic Conduction of Electricity. Thesis in University of Illinois Library, Filed June, 1914.

2. Bridgeman, P.W.

Theoretical Consideration on the Nature of Metallic Resistance with Especial Regard to the Pressure Effect. Physical Review, Vol.9, p 269, April, 1917.

3. Bridgeman, P.W.

The Electrical Resistance of Metals Under Pressure. Proc. Amer. Acad. Arts & Sci., 52, 9, p 573, Feb.,1917.

4. Bridgeman, P.W.

Thermo-Electromotive Force, Peltier Heat, and Thomson Heat Under Pressure. Proc. Amer. Acad. Arts and Sci., 53,4, p 269, Mar.,1918.

5. Bridgeman, P.W.

Electrical Resistance Under Pressure, Including Certain Liquid Metals. Proc. Amer. Acad. Arts & Sci., 56, 3, p 61, Feb.,1921.

6. Bridgeman, P.W.

The Electrical Resistance of Metals. Physical Review, 27, 2, p 161, Feb.,1921.

7. Credner, F.

Alteration of Electrical Resistance of Wires When Subjected to Tension or Torsion. Zeitschr. Phys. Chem., 82, p 457,1913.

8. Drude, P.

The Ionic Theory of Metallic Conduction. Phys. Zeitschr. 1, p 161-165, Jan.,1900.

9. Drude, P.

Electron Theory of Metals. Ann. d. Phys. u. Chem., 3, p 369, Nov.,1900.

10. Giese, W.

Theorie der Electricitätsleitung, Ann. d. Phys. u. Chem., 3, p 576, 1889.

11. Grüneisen, E.

Temperature and Pressure. Verh. D.P. Gesell., 15, p 186,1913.

12. Hall, E.H.

The Resistance of Moving Electrolytes. Phys.Rev., 7, p 246-7, 1898.

13. Jaeger, W. and Dieselhorst, H.

Conductivity for Heat and Electricity. Preuss. Akad. Wiss., Berlin, 38, p 719-726, July, 1899.

14. Kensky, T.

Conduction of Electricity in Metals. Zeitschr. Electro-Chem., 14, p 406-410, 1908.

15. Koenigsberger, T.

Conduction of Electricity. Zeitschr. Electro-Chem. 15, p 97, 1909.

16. Kraus, C.A.

The Temperature Coefficient of Resistance of Metals at Constant Volume and its Bearing on the Theory of Metallic Conduction. Phys.Rev., 2, 4, 159, 1914.

17. Livens, G.H.

The Electron Theory of Metallic Conduction. Phil.Mag., 29, pp 173 and 425-432.

18. Lees, C.H.

The Electronic Theories of the Properties of Metals. Nature,

95, 675-677, 1915.

19. Nabl, J.

Resistance of Electrolytes in Motion. Akad. Wiss. Wien. Sitzb. 108, IIa, p 1538-1558, 1899.

20. Nichols, E.F.

Die Moglichkeit einer durch Zentrifugale Beschleunigung erzengten electromotorischen Kraft. Phys.Zeitschr. p.640, 1908.

21. Richardson, O.W.

Theory of Metallic Conduction. Amer. Electro-Chem. Soc. Trans., 21, p 69, 1912.

22. Reinganum, O.W.

Theory of Metallic Conduction. Ann. d. Phys. u. Chem., 2, 2, p 398-403, 1900.

23. Riecke, E.

Thermal and Electric Conductivities. Ann. d. Phys. u. Chem., 2, 4, p 835, 1900.

24. Riecke, E.

Electric Conduction in Metals. Phys. Zeitschr. 2, p 639, Aug., 1901; Ann. d. Phys. u. Chem., N.F.,66, p 543, 1898.

25. Schenck, R.

Electron Theory. Studies in Metallic Solid Solutions. Ann. d. Physik, 32, 2, p 261-290, May, 1910.

26. Skaupy, F.

Electric Conduction in Metals. Verh. d.D.P. Gesell. 16, p 156-167, Feb.1914.

27. Swann, W.F.G.

Metallic Theory of Conduction. Phil.Mag., Ser.6, 27, pp 441-454, 1914.

28. Starling, S.G.

Electricity and Magnetism. Chapter XVII, p 549.

29. Thomson, J.J.

Conduction of Electricity Through Metals. Phil.Mag., 30, p 192, 1915.

30. Thomson, J.J.

The Conduction of Electricity Through Metals. Nature, 96, pp 494-499, Dec.1915.

31. Thomson, J.J.

Corpuscular Theory of Matter. Chapter IV.

32. Tolman, R.C. and Stewart, T.D.

Electromotive Force Produced by Acceleration of Metals. Phys. Rev., 43, Ser.2, 8, p 97, Aug.1916.

33. Tunzelman, G.W.

A Treatise on Electrical Theory. Chapter XIV.

34. Weber, W.

Weber's Werke, p 294.

35. Wiedeman, G.

Die Lehre der Electricität, 4, p 825.

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